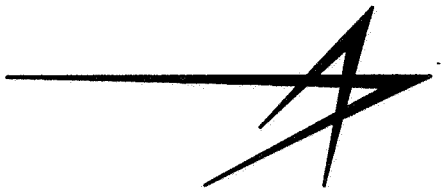

Lack Of Penetration in Friction Stir Welds: Effects on Mechanical Properties and NDE Feasibility

AeroMat 2000 Conference and Exposition Friction Stir Joining: Session 4

June 29, 2000

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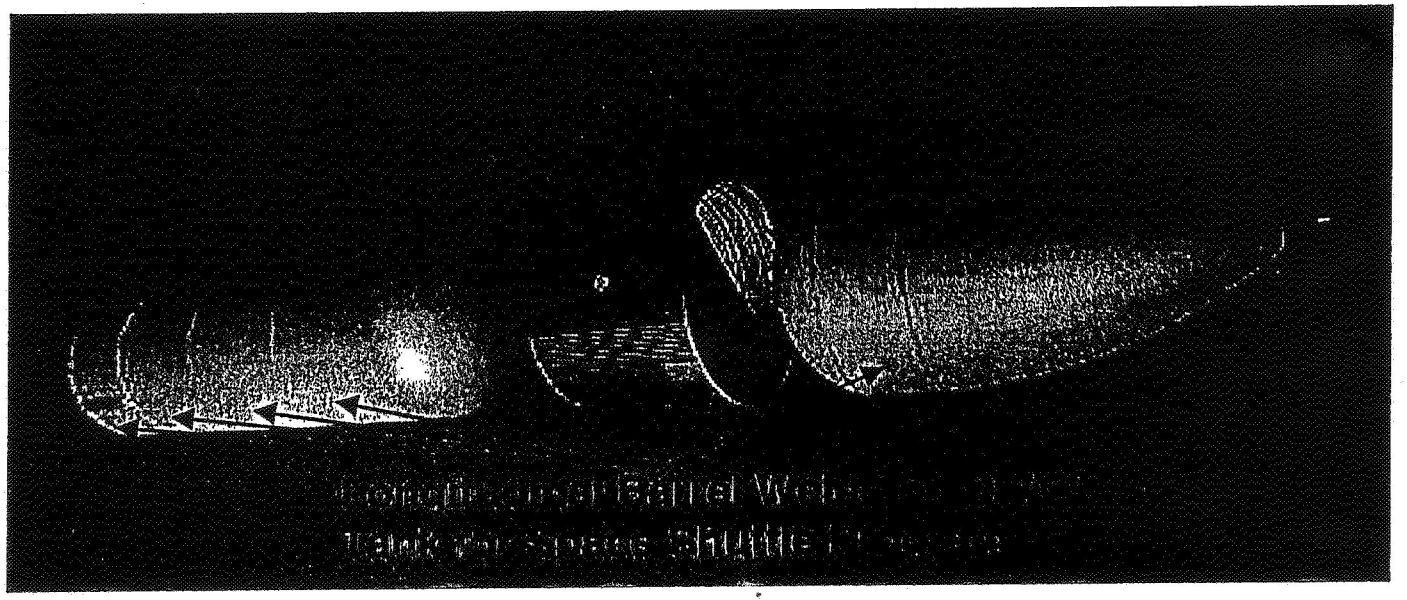
Acknowledgements and Planned Applications

- *NASA funded Special Development Studies 1998 and 1999*
  - MSFC Materials and Processes ED33
  - MSFC Welding facility in Bldg. 4705
  - MSFC NDE support
- *LMMSS*
  - M&P Test Laboratories
  - NDE Development Support
- *Outside Contractors*
  - *JENTEK Sensors, Inc.*
  - *Sonic Systems International & Automated Inspection Systems*
  - *RD/Tech*
  - *Krautkramer*



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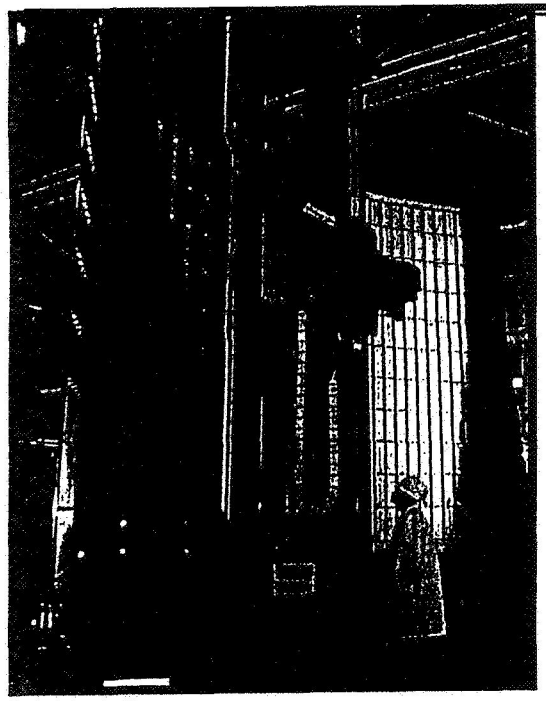
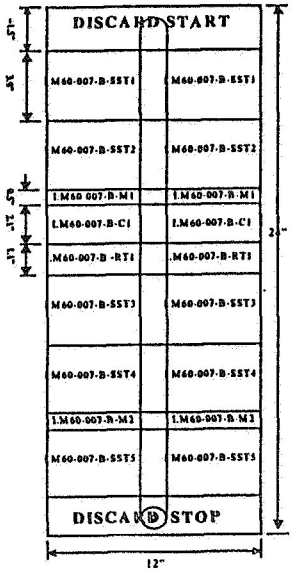
Overview of Development Activities





- *Vertical FSWelder at MSFC Bldg. 4705*
  - 0.32" & 0.65" Al 2195T8M4 Plate
  - RPM, IPM and plunge force varied during weld development experimental designs
  - Confirmation and full scale panels welded
  - Demonstration hardware completed
- *Square Butt Joint 0.32" & 0.65" Thick*
  - Al2195 and Bi Metal, Al2219 to Al2195 Joints
  - Tapered
  - Two-Sided
  - Joint Gap
  - Repair Methods
- *Mechanical Properties Tests*
  - Tensile, yield and elongation at room, cryogenic and elevated temperatures
  - SCT and SST at room, cryogenic and elevated temperatures

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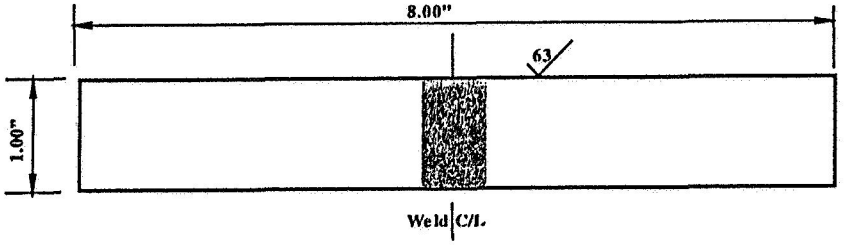
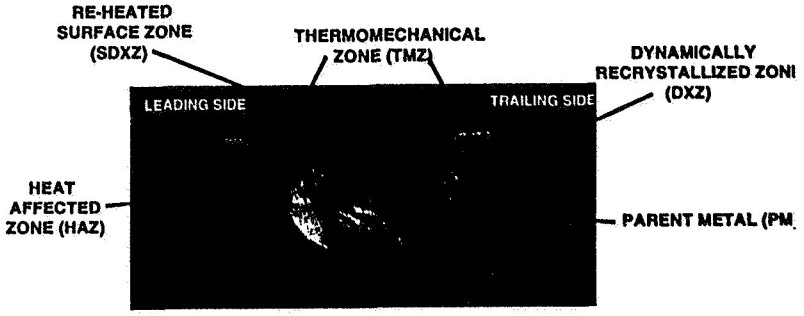
FSWeld Mechanical Properties Specimens & Tests

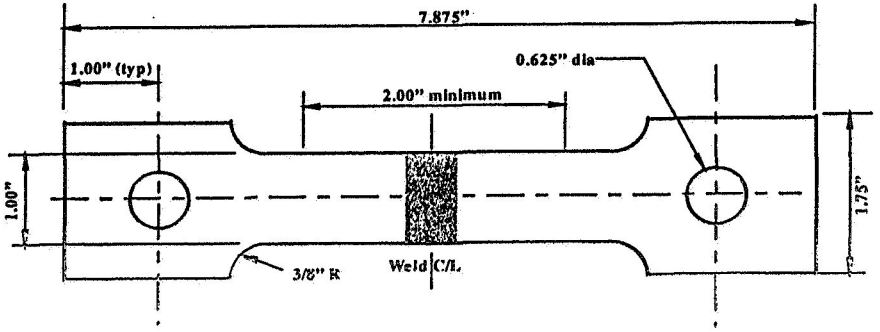
- Room Temperature Tensile Specimen





TYPICAL MICROSTRUCTURE OF FULL PENETRATION FSW WELD IN 0.320"2195-T8M4 PLATE

- Cryogenic & Elevated Temperature Tensile Specimen



- ***Test Temperatures***
  - -423^{0}F
  - -320^{0}F
  - 70^{0}F
  - +200^{0}F
  - +300^{0}F

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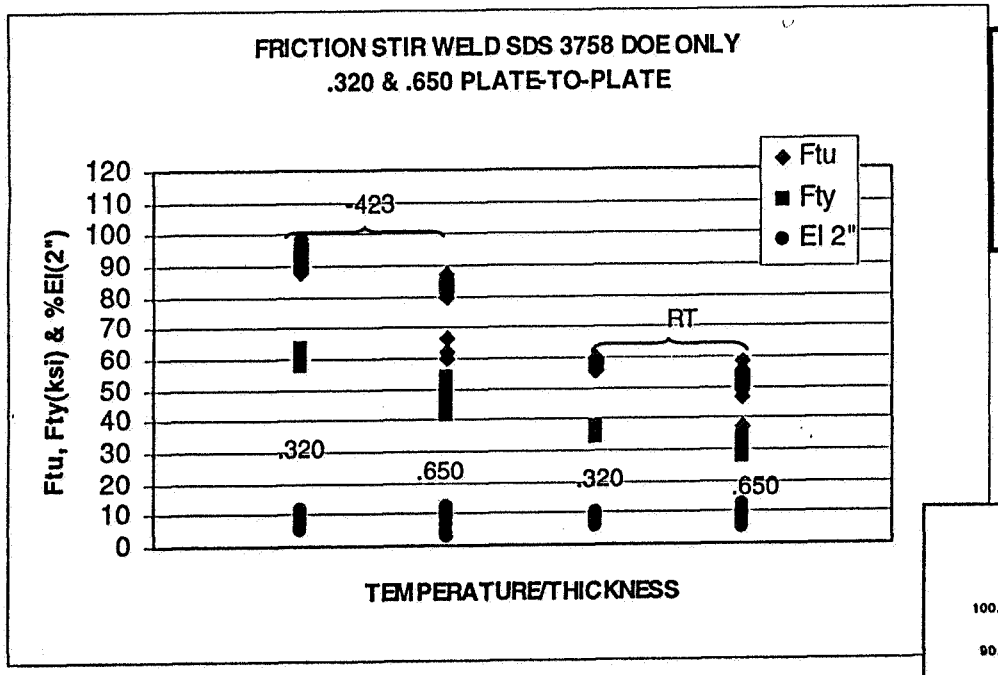
FSWeld Mechanical Properties Test Results

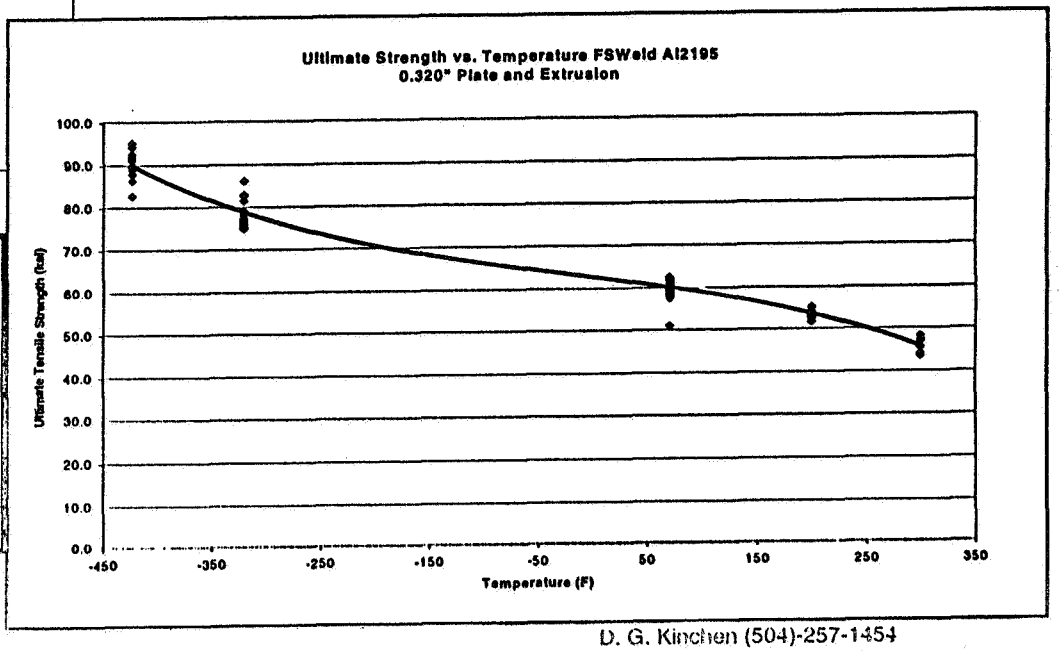


0.320" & 0.650" RT & Cryogenic Tests

- DOE, verification and full-length
- Reduction in strength vs thickness
- Elongation consistent and reproducible

0.320" & 0.650"Cryogenic Enhancement in Strength

- 1.5X Ftu and Fty
- Elongation consistent with RT Elevated temp, Reduction
  - 0.75X Ftu and Fty @ +300F



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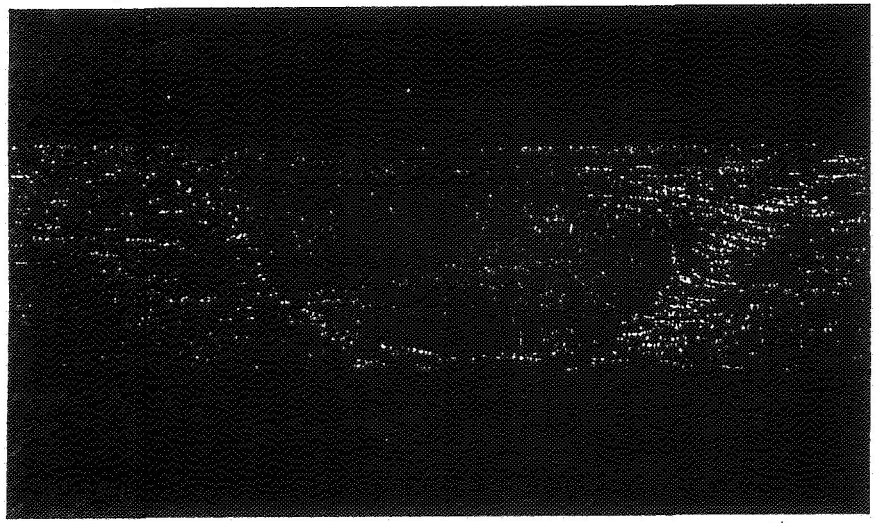
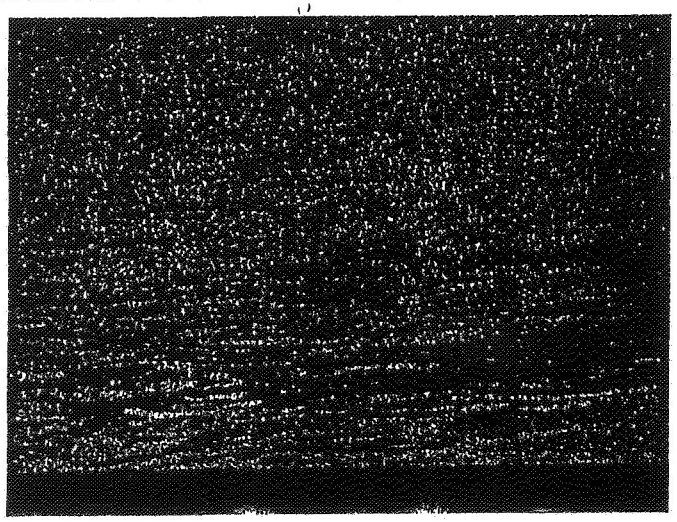
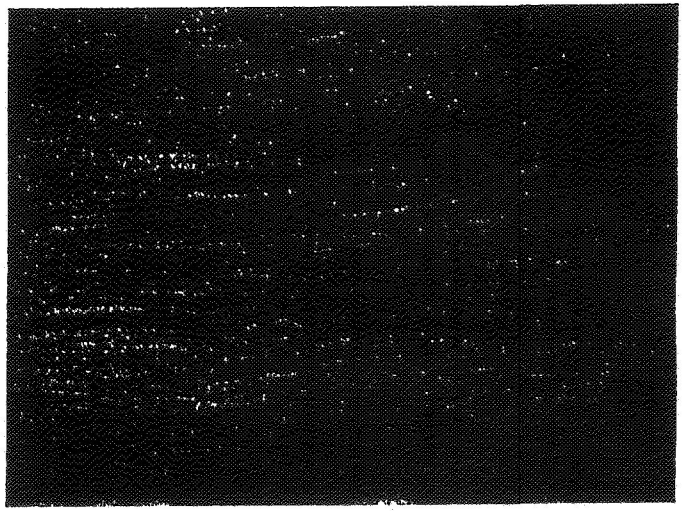
FSWeld Lack Of Penetration



- *LOP - Lack Of Penetration*
  - Root Side of Weldment
  - Surface Breaking Defect
  - Results from incomplete penetration of the DXZ
  - Frequently referred to as "kissing bond"
  - Requires micro examination to detect
  - Range of LOP studied from 0.02 to 0.075"





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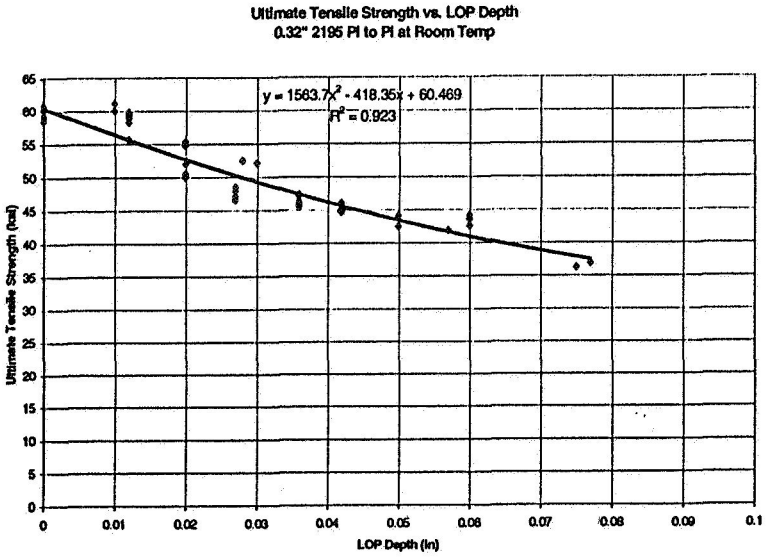
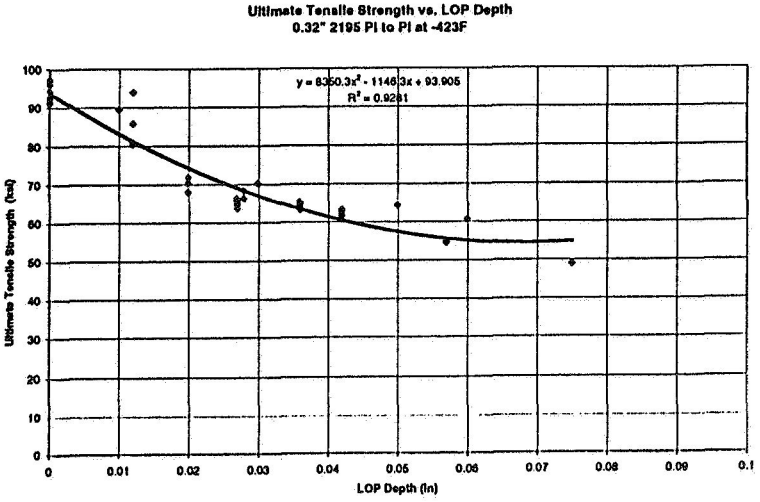
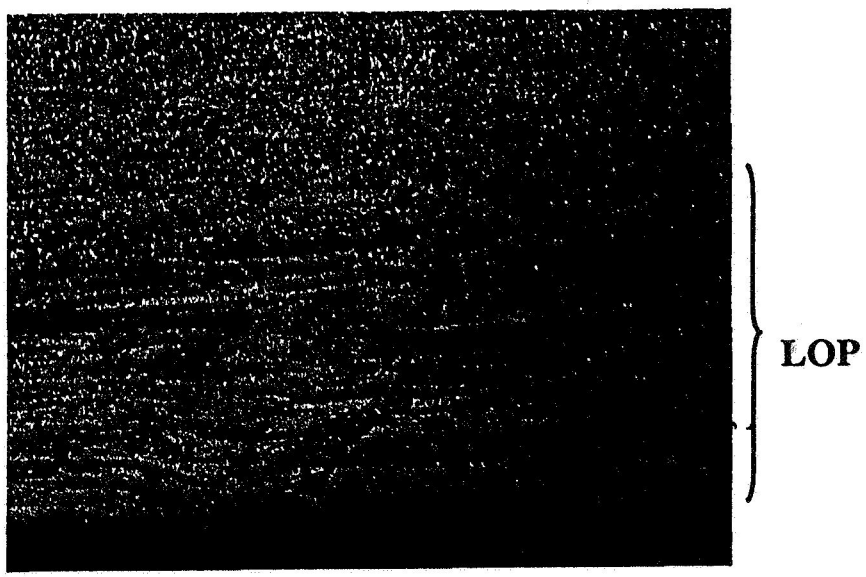
LOP in FSWeld: Mechanical Properties Results







- ***LOP - RT and Cryo Tensile Results***
  - **Consistent, repeatable results**
  - **Predictable as a function of LOP depth**
  - **UTS results compared closely to gross fracture stress at ultimate failure after simulated service tests**

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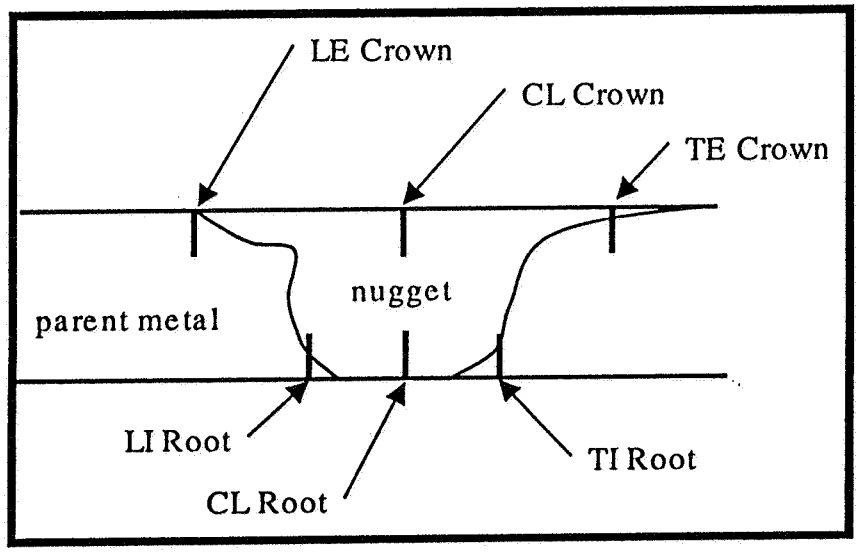
FSWeld Surface Crack Tension Tests



	Target Flaw Size	
a/2c Ratio	a (in)	2c (in)
0.50	0.125	0.250
	0.250	0.500
0.20	0.150	0.750

- Tests conducted at RT, -320F and -423F
- Flaws oriented parallel to the weld direction and perpendicular to the load direction
- Initiated by EDM and increased to size under cyclic axial tension
- CL Crown and CL Root locations demonstrated lowest toughness
- LI and TI Root locations generated wide scatter in toughness data

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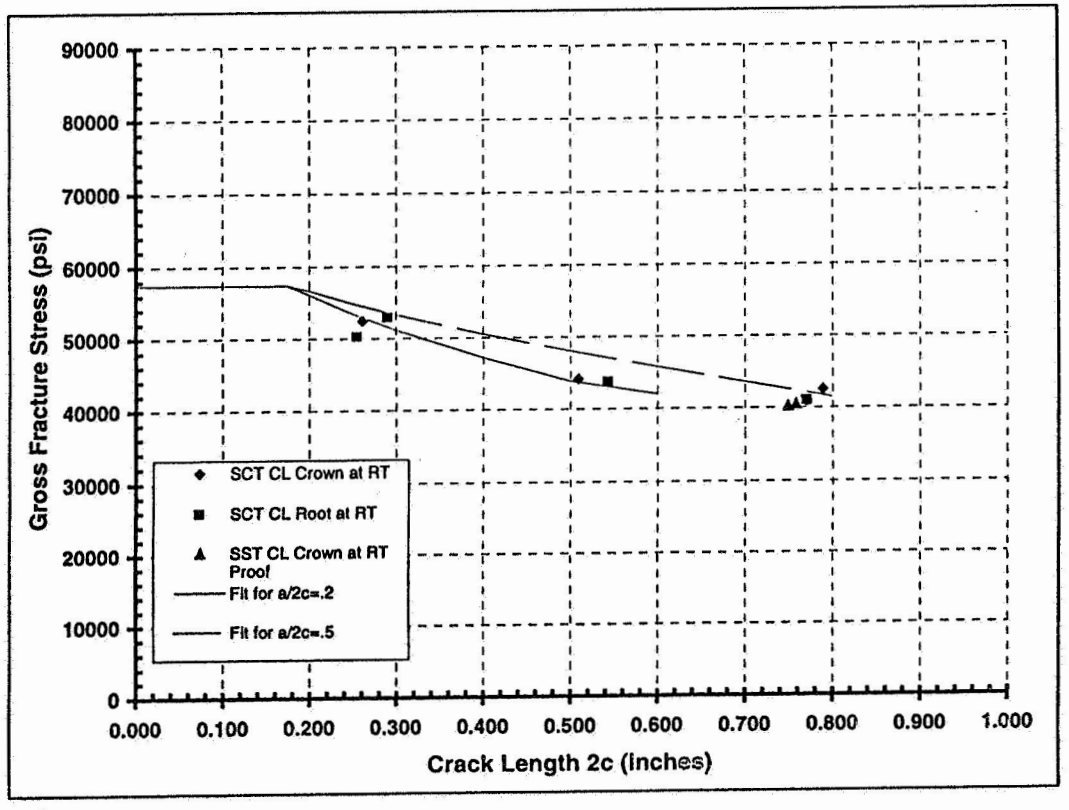
FSWeld SCT Gross Fracture Stress Results



- CL flaw data plotted
- Limited data
- Threshold of 0.180" suggested (a/2c = 0.5 and a/2c = 0.2)
- SST data included

SCT at -320F with LI Root Flaw

SCT at -320F with CL Crown Flaw

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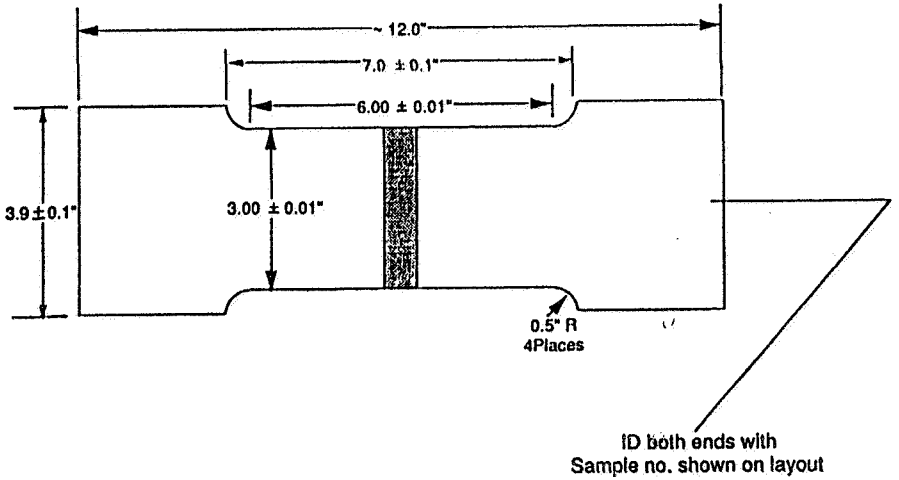
FSWeld Simulated Service Tests

Fracture Specimen

(Use NC Tape F-4)

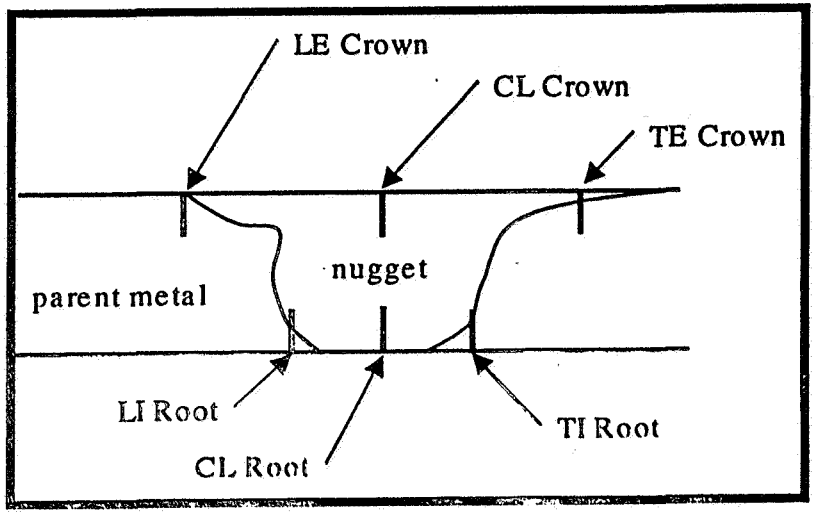


Note

Sawcut dimensions to be 4.0" x 12."

Simulated Service Test Conditions

- **Pre-cracked flaws and natural LOP**
- **Multiple flaw locations**
- **RT, -423^{0}F & +300^{0}F**
- **Multiple RT proof cycles, hold at specified stress, repeated for multiple mission simulation**



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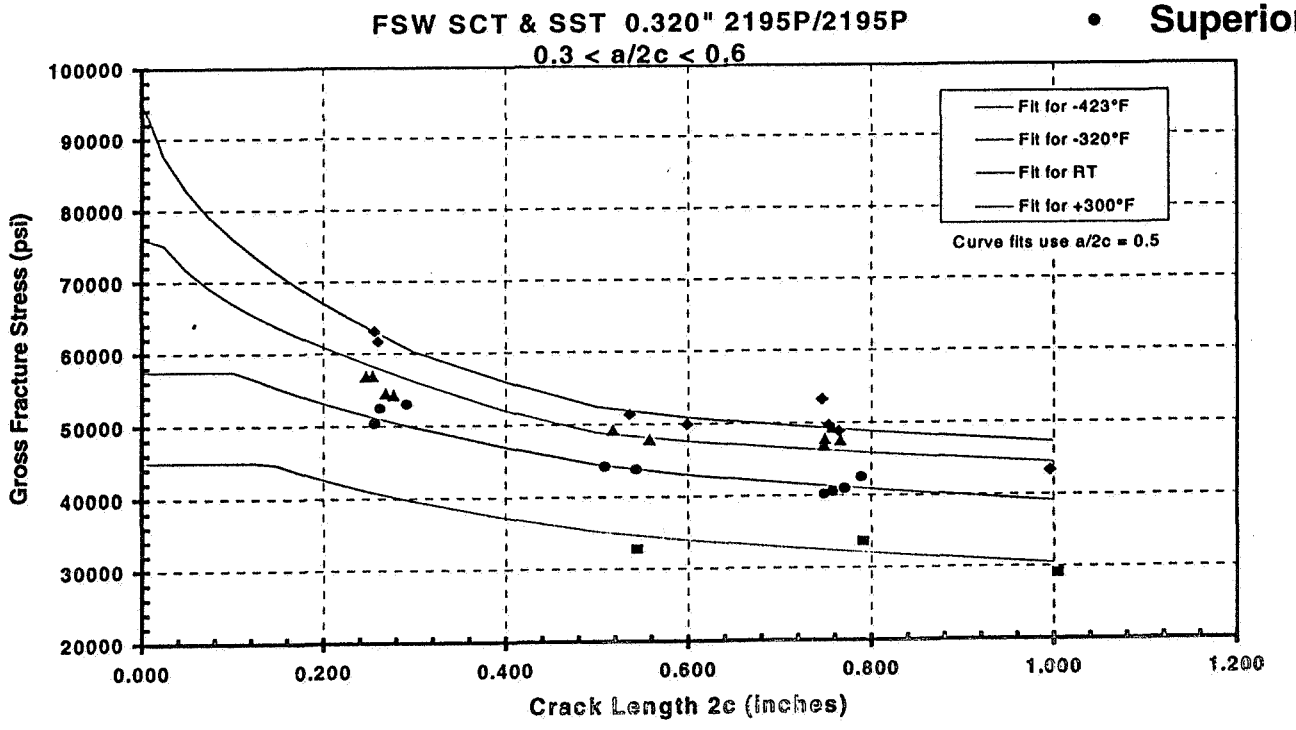
FSWeld Simulated Service Tests Results

- *LOP - SST Results*
  - Consistent, repeatable results
  - Predictable as a function of LOP depth
  - Superior to fusion weld results



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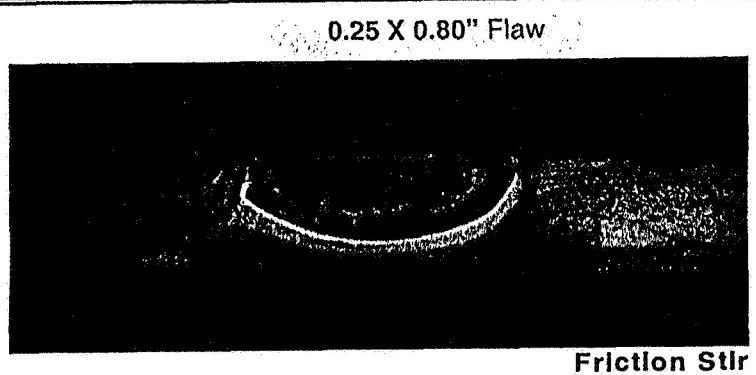
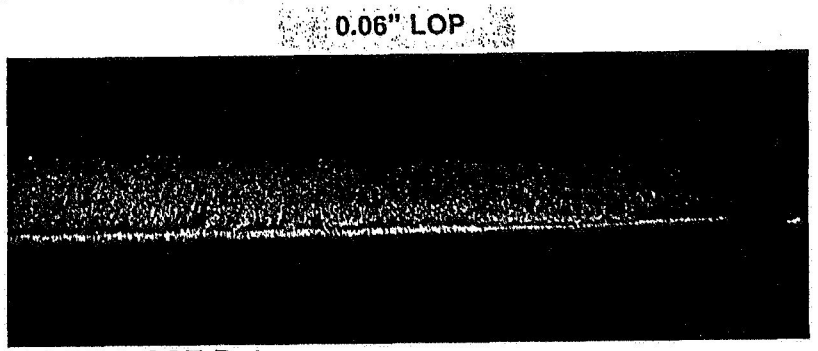
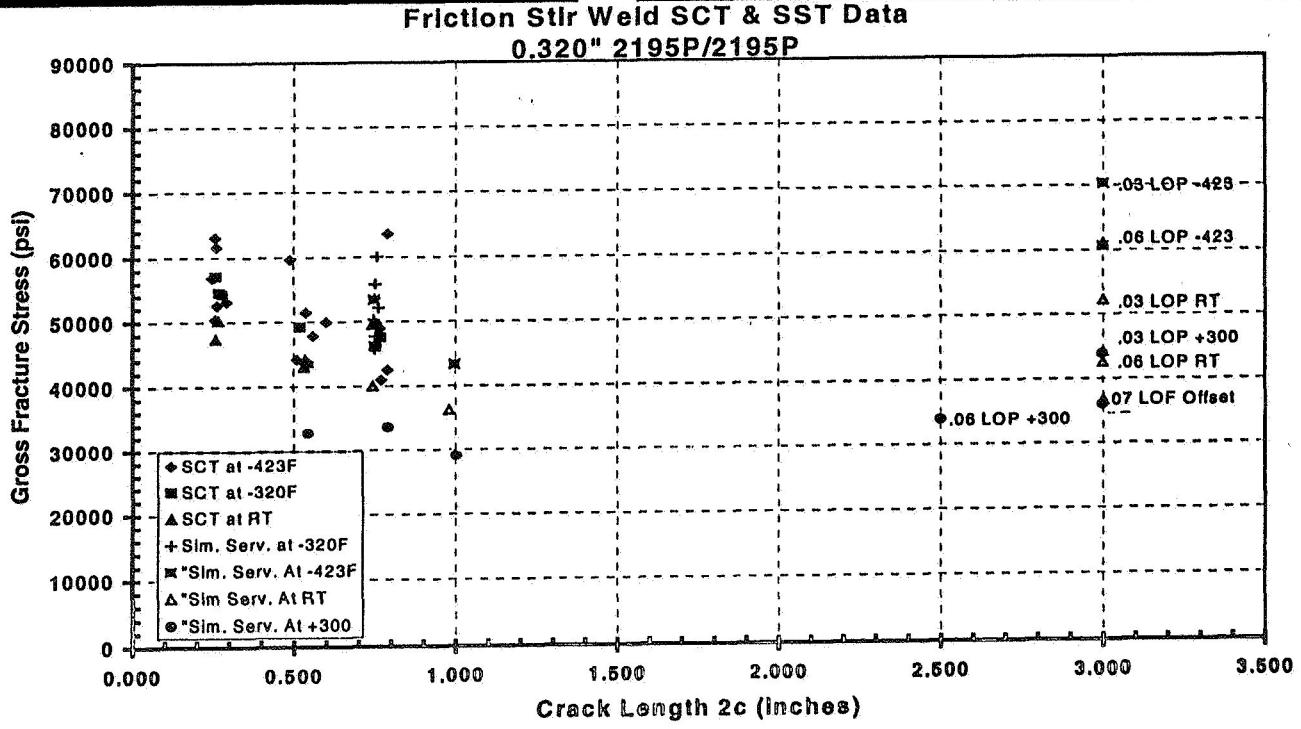
FSWeld Simulated Service Tests Results







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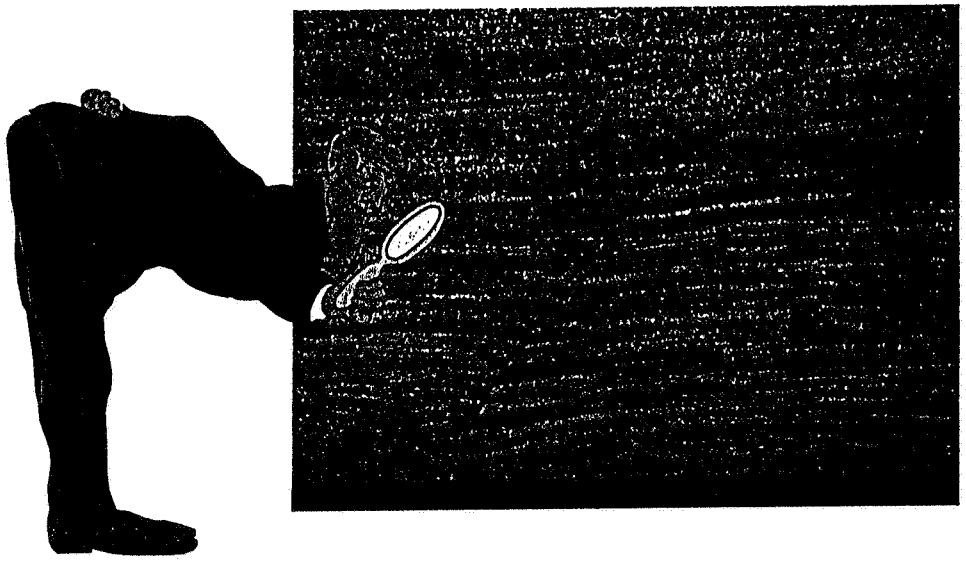
FSWeld NDE Feasibility for LOP Inspection



- *Conventional Eddy Current*
  - Zetec
- *High Sensitivity Eddy Current*
  - MWM sensor
  - Jentek Sensors

- *Conventional Ultrasonics*
  - Contact & Immersion
  - 0, 45 and 60^0 Transducers
  - Shear wave
  - Creeping wave
  - Dual Element
  - Sonic Systems/Automated Inspection Systems
  - Krautkramer
- *Phased Array UT*
  - 64 element array
  - Shear wave
  - R/D Tech

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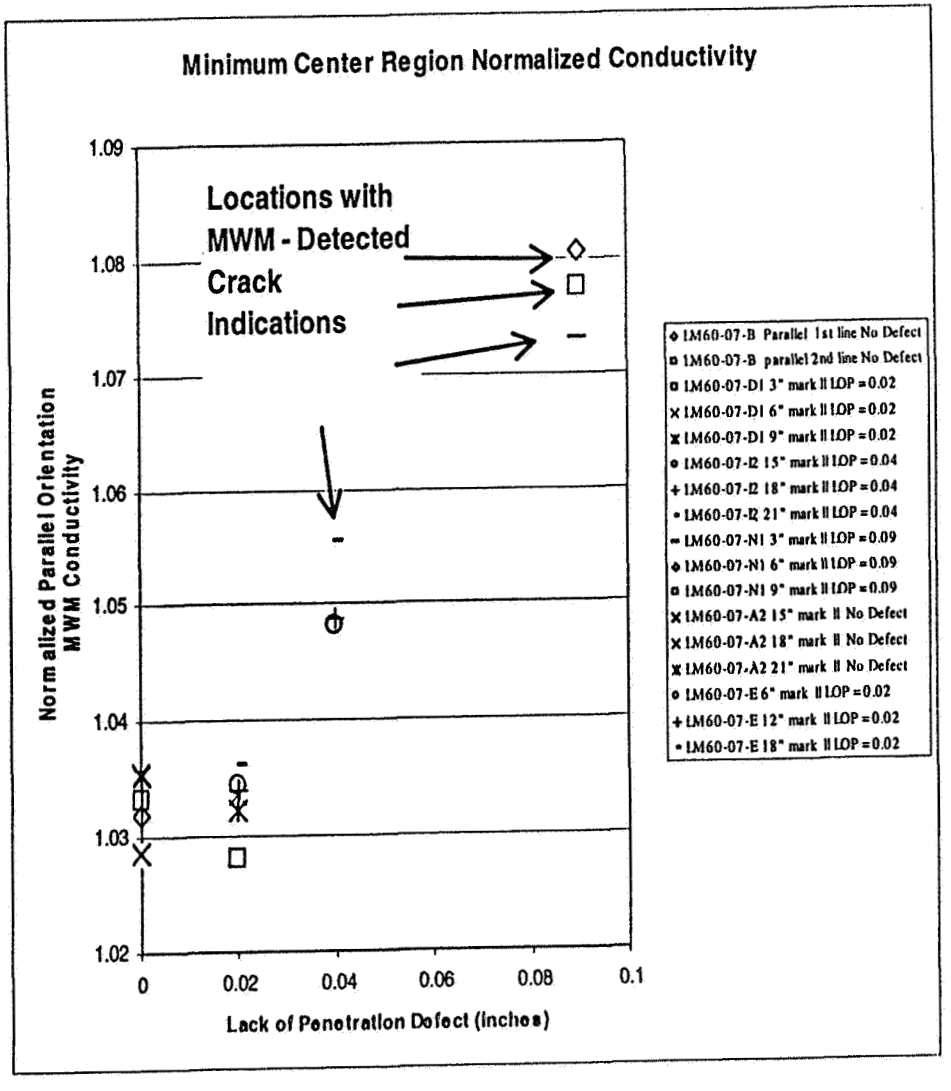
FSWeld NDE Feasibility Results



- ***MWM Eddy Current***
  - **Jentek Sensors, Inc.**
  - **0.040" detected**
  - **Possibility of greater detectability**

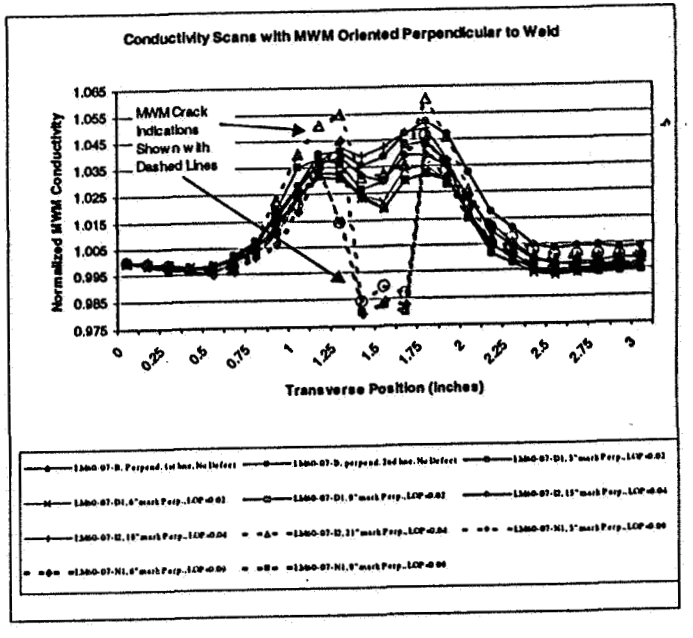


Figure 3: Normalized MWM Conductivity Scans for Friction Stir Weld Specimens, with MWM Oriented Perpendicular to Weld.

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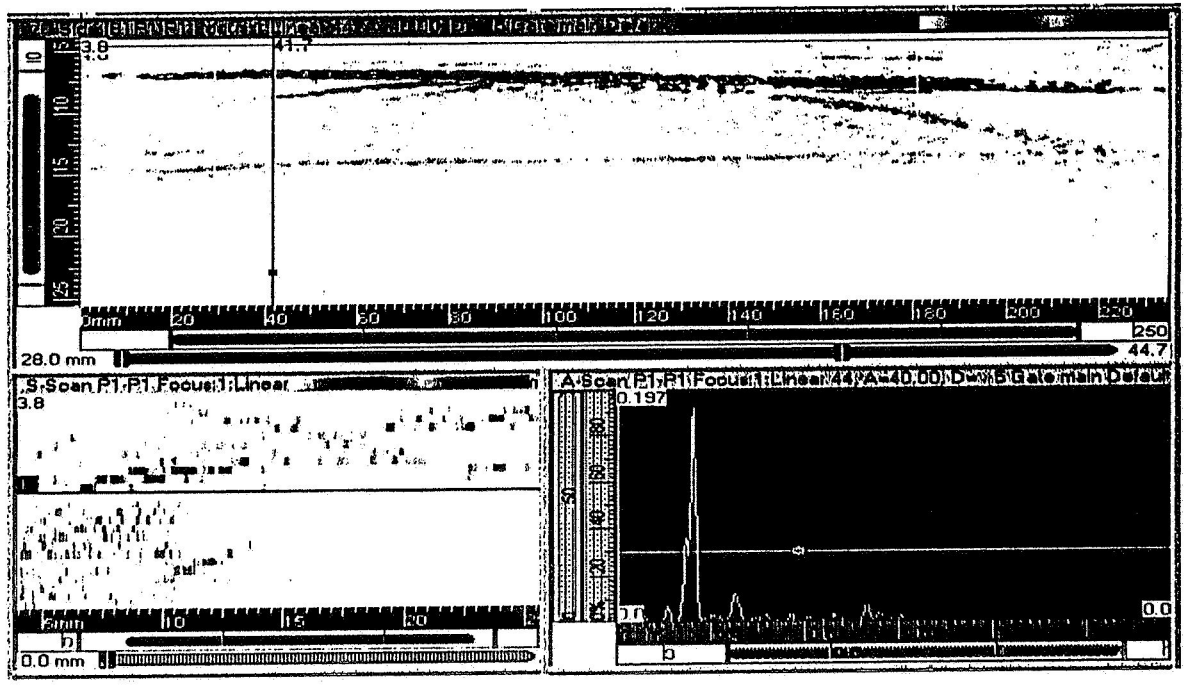
FSWeld NDE Feasibility Results

- ***Phased Array UT***
  - **R/D Tech Inc.**
  - **0.060" LOP results shown**
  - **Possibility of greater detectability**



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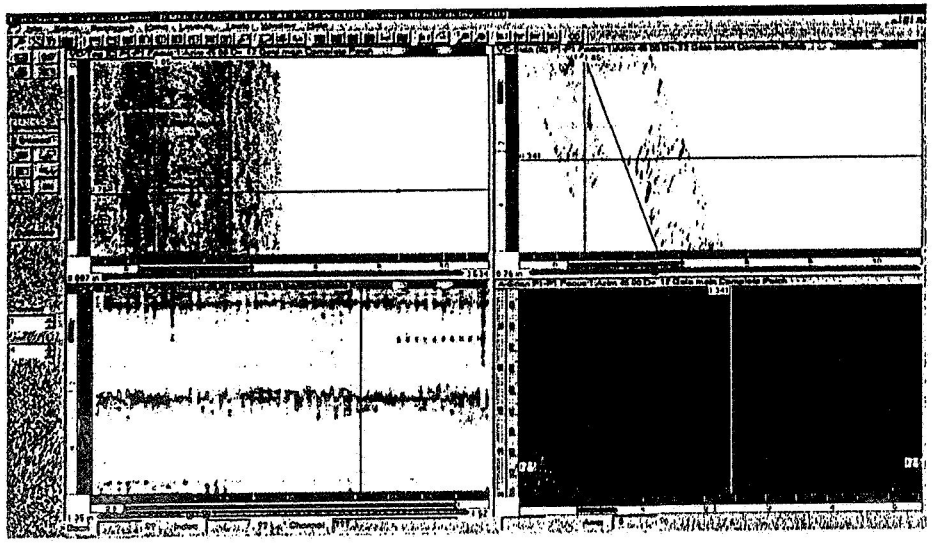
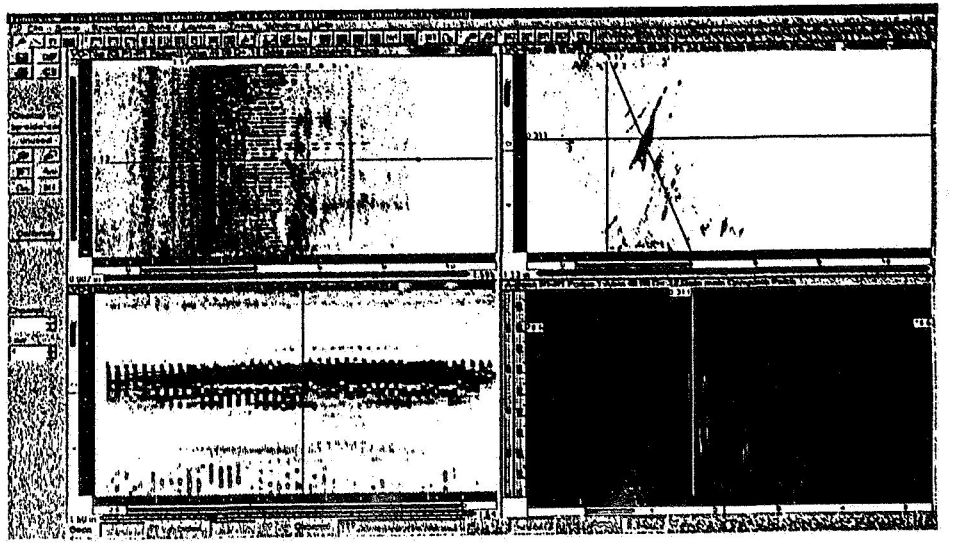
FSWeld NDE Feasibility Results

- ***Phased Array UT***
  - **LMSS Michoud Operations**
  - **0.030" and 0.060" LOP detected post proof**

0.03" deep LOP



0.06" Deep LOP



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Results

- ***Conventional Ultrasonics***

- ***Sonic Systems/Automated Inspection Systems***
  - **Creeping wave and Dual Element FAST probes detected 0.040" LOP intermittently**
  - **Easily detected deep LOP (0.090"**

- ***Krautkramer***
  - **Contact & Immersion 0, 45 and 60^0 Transducers, and Shear wave**
  - **Readily detected 0.060" deep LOP**

- ***Conventional Eddy current***

- ***Zetec***
  - **Readily detected 0.090" LOP, but not 0.040".**
  - **Recommended development of other NDE methods**

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Results

- Mechanical property tests of FSW in 0.320" Al 2195 demonstrated an average RT UTS of 59 ksi, with a cryogenic enhancement factor of 1.5 and elongation of ~10%. All of these values are above those currently attainable with fusion weld processes. 0.650" Al 2195/Al 2219 FSWelds average RT UTS is 47 ksi with similar cryo enhancement and elongation.
- Lack Of Penetration is NOT an inherent condition in FSWelds of Al 2XXX alloys. Adequate process controls preclude LOP.
- SCT and SST tests of induced cracks resulted in gross fracture stress values above the values associated with current fusion weld processes.
- Tensile and fracture test results of LOP indications demonstrate predictable results well above comparable fusion welds at RT, cryogenic and elevated temperatures .
- Multiple NDE techniques exist or have shown feasibility to detect LOP in FSWelds.

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